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Exact Landau Fluid Equations

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We derive a set of exact Landau fluid equations, making no approximation regarding nonlinear kinetic interaction. Prior such equations[1,2] include a model for only *linear* wave-particle resonances. However, there has been concern that this inaccurately treats *nonlinear* kinetic effects, such as wave-particle scattering or trapping.[3,4,5]

We start with the drift kinetic equation in a straight slab with Maxwellian equilibrium,

$$\left(\omega - k_{\|}v_{\|}\right)\widetilde{f}_{\mathbf{k}} - \left[k_{\|}v_{\|} - \omega_{*} + \omega_{*}^{T}\left(\tfrac{3}{2} - \tfrac{1}{2}v^2\right)\right]F_M\widetilde{\phi}_{\mathbf{k}} - \sum_{\mathbf{k}'}\widetilde{\mathbf{v}}_{E,\mathbf{k}''}\cdot\mathbf{k}'\widetilde{f}_{\mathbf{k}'} \;=\; 0.$$

Fluid closure is accomplished by expanding $\widetilde{f}_{\mathbf{k}}$ in Hermite polynomials, solving analytically for the higher coefficients in terms of the second coeffiecient, and using this solution to evaluate higher moments in terms of lower. This gives the following temperature equation:

$$-i\omega\widetilde{T}_{\|,\mathbf{k}} - i\omega_{*}^{T}\widetilde{\phi}_{\mathbf{k}} + 2ik_{\|}\widetilde{V}_{\|,\mathbf{k}} + \sum_{\mathbf{k}'}\widetilde{\mathbf{v}}_{E,\mathbf{k}''}\cdot i\mathbf{k}'\widetilde{T}_{\|,\mathbf{k}'} + ik_{\|}\sum_{\mathbf{k}'}G_{\mathbf{k},\mathbf{k}'}\widetilde{T}_{\|,\mathbf{k}'} = 0,$$

where the Landau fluid heat flux is:

$$G_{\mathbf{k},\mathbf{k}'} \equiv -\overrightarrow{e}_{\mathbf{k}}\left[Z_0'''(\overleftrightarrow{W}/\sqrt{2})/\sqrt{2}Z_0''(\overleftrightarrow{W}/\sqrt{2})\right]\overleftarrow{e}_{\mathbf{k}'}$$

Z_0 is the plasma dispersion function, $v_{\mathbf{k}} \equiv \omega/k_{\|}$, and $\widetilde{u}_{\mathbf{k},\mathbf{k}'} \equiv \widetilde{\mathbf{v}}_{E,\mathbf{k}-\mathbf{k}'}\cdot\mathbf{k}'/k_{\|}$, $\overrightarrow{e}_{\mathbf{k}}\overleftrightarrow{W}\overleftarrow{e}_{\mathbf{k}'} \equiv v_{\mathbf{k}} - \widetilde{u}_{\mathbf{k},\mathbf{k}'}$, $\overrightarrow{e}_{\mathbf{k}}$ and $\overleftarrow{e}_{\mathbf{k}'}$ are unit row and column vectors for modes $\mathbf{k}$ and $\mathbf{k}'$. For non-degenerate $\overleftrightarrow{W}$, the operators $Z_0(\overleftrightarrow{W})$ can be evaluated by an eigenvalue representation. To evaluate time evolution of a complicated function of frequency $G_{\mathbf{k},\mathbf{k}'}$, we introduce a numerical scheme where the frequencies are evaluated in terms of the previous time step, $\omega_{\mathbf{k}} \simeq i(\partial_t\widetilde{T}_{\|,\mathbf{k}})/\widetilde{T}_{\|,\mathbf{k}}$.

Work is currently underway to determine whether these equations repair previously discovered discrepancies between Landau fluid and kinetic theories.

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1. G. W. Hammett and F. W. Perkins, Phys. Rev. Lett. **64,** 3019 (1990).
2. Z. Chang and J. D. Callen, Phys. Fluids B **4,** 1167 (1992).
3. N. Mattor, Phys. Fluids B **4,** 3952 (1992).
4. S. E. Parker *et al.*, Phys. Plasmas **1,** 1461 (1994).
5. A. M. Dimits *et al.,* Phys. Rev. Lett. **77,** 71 (1996).

PREFER ORAL

Synthetic Experimental Diagnostics: A Simulation Example*

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The CORSICA equilibrium, transport, and stability modeling code is being extended to include simulation models of experimental diagnostics. Diagnostic systems are often significant experiments within an experiment. Understanding the performance of fusion experiments is based on conclusions and inferences derived from the diagnostic measurements. Therefore, in order to better understand the physics of the diagnostics, to increase confidence in the inferences based on the diagnostics, to make direct comparisons with experiments easier, and, hence, to model experiments more comprehensively, we are adding simulation models for a suite of selected diagnostics to CORSICA. The first example diagnostic is reflectometry, which is used to infer density and magnetic field spatial profiles. Simulation models of O and X-mode reflectometry[1] are being added to CORSICA as packages. The reflectometry simulation models consist of full-wave solutions for the electromagnetic wave propagation in a cold plasma and geometric optics reconstruction packages to infer the density and magnetic field profiles. Examples of reflectometry simulations for DIIID and the Livermore spheromak experiment (under development) executed from within CORSICA transport simulations are presented.

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[1] B. I. Cohen, B. B. Afeyan, A. E. Chou, and N. C. Luhmann, Jr., Plasma Phys. Control. Fusion **37**, 329 (1995); B. I. Cohen, T. B. Kaiser, and J. C. Garrison, accepted by Rev. Sci. Instrum.

Development of Implicit 3D Fluid Turbulence Code in SOL Plasmas with X-Point Geometry*

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During to the complication of magnetic shear, we are unable to conduct 3D simulations with real x-point geometry in our simulation code using an explicit time advance scheme. We are currently reprogramming the code by using implicit CVODE/PVODE PDE integrator. CVODE/PVODE is a solver for stiff and non-stiff initial value problems for systems of ordinary differential equation. The robust preconditioned iterative integrator has been demonstrated in the UEDGE transport code. We have tested this PDE integrator in our 2D non-local Hasagawa-Wakatani code for the parameter $\alpha >> 1$ and have obtained saturated states on a reasonable time scale short compared to our previous explicit code. The implementation of real x-point geometry and the electron inertia will be discussed. The effects of magnetic shear and electron inertia on the turbulence will be reported.

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Detached Divertor Plasmas with Time Variation*

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Detached divertor plasmas are studied using the time-dependent mode of the UEDGE 2-D fluid transport code. The two-fluid Braginskii equations describe the hydrogenic plasma with anomalous cross-field transport and a reduced Navier-Stokes model describes the neutral gas. Impurities are represented by either fixed-fraction or multi-charge state models. Steady-state solutions are generally found for moderate impurity levels. These plasmas can exist with no particle throughput for the system. As the radiation loss from impurities is increased, the plasma particle and energy fluxes to the plate are drastically reduced. As this detached plasma mode becomes more pronounced, an ionization front moves upstream from the plate and steady-state solutions become more difficult to find. We expand our analysis of these detached plasmas to include time-dependent solutions and find two types: One has a small, but finite, particle throughput for the system with inflow from the core and outflow near the divertor plate which produces delicate steady-state solutions when balanced. The second state has no particle throughput and results in periodic temporal oscillations of the plasma which can change from weakly attached to detached over the course of the oscillation. A MARFE under the x-point can play an important role in these oscillations which may be the extension to detached plasmas including impurities of oscillatory divertor-plasma solutions described previously.[1] The general behavior described above is found for either impurity model. The effect of gas puffing and pumping at various locations is analyzed as a means of controlling the detached plasma for the DIII-D and ITER tokamaks.

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* Work performed for the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

[1] S.I. Krasheninnikov, A.S. Kukushkin, *et al.*, Nucl. Fusion **27**, 1805 (1987).

CORSICA: A Comprehensive Tokamak Simulation Code *

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The CORSICA project has developed a prototype comprehensive simulation code for toroidal magnetic fusion devices. Our goal was to build an efficient simulation on the slow transport timescale by exploiting time and space scale disparities. The project concentrated on three coupling problems: (1) coupling core transport to the quasi-static solution of the free-boundary ideal MHD equilibrium problem (based on the TEQ equilibrium code) and to the evolution of the circuit equations for the poloidal field coils and passive structure; (2) coupling core transport to a 2-D fluid edge transport calculation (the UEDGE code); and (3) coupling core transport to a 3-D turbulence simulation code (the Gryffin toroidal ITG code). In order to solve these coupled systems together in an efficient manner, special coupling algorithms were developed, tested in prototypes, and finally implemented in the CORSICA simulation code. In this paper we will give an overview of the project's accomplishments, discuss applications of the CORSICA simulation code, discuss current work being done by the group, and present our plan for future development in this area.

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ISSUES IN NONLINEAR GYROKINETIC SIMULATIONS OF TOKAMAK TURBULENCE AND TRANSPORT[1]

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We extend our earlier three-dimensional nonlinear gyrokinetic simulations of ITG turbulence in TFTR[2] and DIII-D[3] in directions that have impact on predictions for experiments and comparisons with gyrofluid simulations. (A) Convergence tests of the gyrokinetic simulation results with respect to particle number, spatial resolution, and system size have been undertaken. These tests use much larger simulation runs than were possible in our earlier studies and are made possible by a massively parallel version of our gyrokinetic code. Initial results[3] indicated that the spatial smoothing of the mesh gyrocenter density (which sets the spatial resolution) has a significantly smaller effect on gyrokinetic simulation results than has been reported when such smoothing is applied to gyrofluid simulations.[4] The implication is that spatial smoothing does not explain why gyrofluid simulations give higher transport rates than do gyrofluid simulations. These and additional results will be reported in detail. (B) New simulation runs have been made that extend the number of discharges (both TFTR and DIII-D), times per discharge, and radial points per profile that our simulations address directly. In particular, the sensitivity to temperature gradient of the ion-thermal transport rate for a range of base points and its implications for the range of predicted temperature profiles given the ion heat flow are examined. (C) A commonly used model of the effect of toroidal velocity shear on ion thermal transport involves a relative reduction proportional to the ratio of the $\boldsymbol{E} \times \boldsymbol{B}$ shearing rate to the maximum linear growth rate. However, our simulations have shown[2] that the parallel component of the velocity shear can negate the $\boldsymbol{E} \times \boldsymbol{B}$ stabilization, and that whether or not toroidal velocity shear is stabilizing depends significantly on the ratio of the poloidal and toroidal components of the magnetic field. We report further simulation results that quantify this threshold and examine selected TFTR and DIII-D discharges for evidence of this effect.

We also report issues that arise in and progress on the implementation of a new bounce-averaged drift-kinetic nonlinear-δf electron model. This model differs from earlier work in that it uses one simulation particle per bounce center and the transformations between bounce-center space and the "real" configuration space are handled through field operations.

[1]This work was performed for USDoE, by LLNL under contract W-7405-ENG-48.
[2]A.M. Dimits *et al.*, PRL **77**, 71 (1996).
[3]A.M. Dimits, Bull. APS **41**, 1413 (1996, paper 2IB3).
[4]ibid, p. 1412, paper 2IB2.

SOL instabilities and anomalous transport localized in divertor legs

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The presence of a sufficiently strong instability localized in the divertor legs (i.e., not involving the area above the X-point) could help in reducing the heat flux on the divertor plates (by increasing the thickness of the SOL in the divertor legs) without causing any enhanced transport through the last closed flux surface. The possibility for such modes to exist is related to the fact that, for the flute-like modes, extremely strong shear near the divertor X-point [1] makes the communication between the divertor legs and the rest of the SOL very difficult, unless some special conditions are satisfied [2].

In the present paper we analyse drift-type modes with such a localization. The modes are sensitive to the sheath boundary conditions at the divertor plate, and, in particular, to the angle between the plate and the magnetic field. We use a general form of the sheath boundary condition that includes non-steady-state effects and effects of spatial dispersion. We describe the strongly-sheared X-point region phenomenologically, by introducing an "effective resistance". This resistance establishes a link between the cross-field potential difference and the current through the ends of the flux-tube.

We find the mode structure, frequencies and growth rates for the most unstable perturbations and speculate with regard to possible magnitude of the transport induced by these modes. This work was carried out under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

[1] D. Farina, R. Pozzoli, D. Ryutov. Nucl. Fusion, 33, 1315 (1993).

[2] R.H. Cohen, D.D. Ryutov. Contrib. Plasma Phys., 36, 161 (1996)

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Toroidicity effects and induced convection in the tokamak SOL

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We study a plasma equilibrium in the open field line region of a tokamak scrape-off-layer (SOL). For a toroidally-symmetric configuration, we base our analysis on a representation of the plasma current as a superposition of two non-orthogonal vectors, a toroidal current and a parallel (to the magnetic field) current. We consider effects of parallel plasma flow and the pressure anisotropy on plasma equilibria. We find a broad class of equilibria where the parallel current between the divertor plates is absent.

We then introduce an external force acting on the plasma, representing friction from neutral particles. We assume that it is parallel to the magnetic field. We find that, for the toroidally symmetric situation, the presence of this force still allows static equilibria with no parallel current. If the neutral density is large enough, the plasma resistivity in the vicinity of the divertor plates is so high that the absence of a parallel current at the divertor plates becomes a natural requirement. We call such regimes "electrically detached regimes".

In the rest of the paper, we consider phenomena that appear if the friction force is varying in the toroidal direction. We find that, in the "electrically detached regimes", strong enough toroidal variations lead to impossibility of static equilibria with radially decreasing plasma pressure, unless very artificial assumptions regarding the distribution of heat and particle sources over the SOL are made. Static equilibria are then replaced by convective equilibria, with rapid heat and particle mixing across the magnetic surface. This conclusion may give rise to a practically realizable technique of reducing power loads at the divertor plates.

We discuss the optimum way of creating necessary non-uniformities by toroidally-asymmetric gas puffing. We show that the strongest toroidal variations of the friction force can be created if the gas streams are collimated by the limiters aligned with the field lines.

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Edge plasma in a spheromak

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The results of a preliminary analysis of the properties of the edge plasma in the Livermore Spheromak are reported. The main emphasis in this study was made on the plasma behavior on the open field lines, during the quasi-steady phase of the discharge (after the spheromak had been ejected from the gun to the flux-conserver). It has been shown that the main source of plasma heating is the Joule dissipation of the current flowing from one electrode to another. The main channel of heat losses is electron thermal conductivity to the walls. The balance of these two processes sets the plasma temperature on the open field lines. For the design parameters of the Livermore Spheromak one can expect the temperature and density in the range 20-30 eV, and 10^{14} cm^{-3}, respectively (in the middle of the field line ending on the opposite electrodes). Cross-field transport plays a subdominant role in the bulk of the open-field-line region. Therefore, field lines that begin and end at electrode surfaces of the same polarity (such field lines may appear because of the field errors, because of the skin effect, and, in some cases, by intention) are devoid of warm plasma. Impurity radiation does not play a significant role in the thermal balance on the open field lines (although the absolute value of the radiated power may be high, in the range of a few MW).

The role of the skin effect in the walls of the flux conserver has been analysed. The skin effect may lead to formation of a central plasma column that leans on the upper and lower plates of the flux conserver (the axis of the device will be vertical). The line-tying effect may provide additional stabilization to the global tilt and shift modes.

The expected current density is well above the ion saturation current for field lines which contact surfaces outside the gun barrel. This means that the current is carried predominantly by the electrons. For the open field lines this means also that the cathode should emit enough electrons, and/or that there should be a high density of cold plasma near where the field lines intersect material surfaces. The processes on the plasma-cathode interface are briefly discussed. The conclusion is drawn that one can expect sufficient electron emission in the Livermore Spheromak.

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